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NEVER SMOKER LUNG CANCER RISKS FROM EXPOSURE TO PARTICULATE TOBACCO SMOKE

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The average particulate environmental tobacco smoke (ETS) exposure of never and current smokers and the average lung cancer mortality rate for current smokers is estimated from empirical data. These estimates are used in a linear downward extrapolation of the lung cancer risk/mg of particulate ETS exposure for current smokers to calculate the average lung cancer risk for never smokers and the number of never smoker lung cancer deaths (LCD) in the U.S. in 1980 from exposure to particulate ETS. The estimated average daily inhaled particulate ETS exposure for never smokers is 0.62 mg/day for men and 0.28 mg/day for women. The average never smoker is estimated to retain 11% of the inhaled exposure, for a daily retained exposure of 0.07 mg for men and 0.03 mg for women. Other estimates are: **a daily retained exposure for current smokers of 310 mg for men and 249 mg for women, a smoking-attributable lung cancer risk for current smokers in 1980 of 284 LCD/100,000 men and 121 LCD/100,000 women, and** an annual retained-exposure lung cancer risk for never smokers of 0.64 LCD/100,000 men and 0.015 LCD/100,000 women. These risks and exposures estimate 12 lung cancer deaths among never smokers from exposure to particulate ETS: 8 among the 11.96 million male never smokers and 4 among the 28.85 million female never smokers in the U.S. in 1980. Conversely, between 655 and 3,610 never smoker lung cancer deaths are estimated from methods based on the average lung cancer risk observed in epidemiological studies of exposure to ETS. Three possible reasons for the discrepancy between the exposure and risk-based estimates are discussed: the excess risks observed in epidemiological studies are due to bias, the relationship between exposure and risk is supralinear, or sidestream tobacco smoke is substantially more carcinogenic than an equivalent exposure to mainstream smoke.

Introduction

Never smokers can be passively exposed to tobacco smoke at work, at home, and in public areas such as shopping centers and restaurants, particularly if the ventilation is poor. Concern over the average never smoker's lung cancer risk from exposure to "environmental" tobacco smoke (ETS) has grown considerably since a 1981 study reported an association between lung cancer in nonsmokers and marriage to a smoker (Hirayama, 1981). Since then, other epidemiological studies of the association between lung cancer among nonsmokers and ETS exposure from living with a smoker have been conducted in Japan (Akiba *et al.*, 1986), Greece (Trichopoulos *et al.*, 1983), Hong Kong (Chan & Fung, 1982; Koo *et al.*, 1985), Sweden (Pershagen *et al.*, 1987), Great Britain (Gillis *et al.*, 1984; Lee *et al.*, 1986), and the U.S. (Garfinkel *et al.*, 1981; Correa *et al.*, 1983; Buffler *et al.*, 1984; Kabat & Wynder, 1984; Garfinkel *et al.*, 1985; Dalager *et al.*, 1986; Brownson *et al.*, 1987; and Humble *et al.*, 1987). The results of these studies have been used to estimate an average excess lung cancer risk for never smokers of 30% from ETS exposure (Blot & Fraumeni, 1986; NRC, 1986; Wald *et al.*, 1986; Wigle *et al.*, 1987). Alternatively, the risk can be estimated by downward extrapolation techniques based on the lung cancer risk for current smokers and the average exposure of current and never smokers. The former method is a risk-based estimate whereas the latter is an exposure-based estimate.

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Linear Extrapolation

This study uses linear downward extrapolation to estimate the lung cancer risk and the number of U.S. lung cancer deaths for male and female never smokers in 1980 from exposure to ETS. The final estimate of the number of ETS-attributable never smoker lung cancer deaths requires four preliminary estimates:

1. The number of never smokers at risk,
2. The average tobacco smoke exposure of never smokers,

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3. The average tobacco smoke exposure of current smokers, and
4. The smoking-attributable lung cancer risk for current smokers.

The lung cancer risk for never smokers is estimated by dividing the lung cancer risk for active smokers by the ratio of the average tobacco smoke exposure of smokers and never smokers. The estimated lung cancer risk for never smokers is then used to predict the number of ETS-attributable never smoker lung cancer deaths in the U.S. in 1980. This is done by multiplying the estimated lung cancer risk for each sex by an estimate of the total U.S. population of never smokers of each sex $\geq$ 35 years of age. Appendix A lists the equations and parameters used in the linear extrapolation estimate.

Estimating the smoker/never smoker exposure ratio

The major difficulty with the extrapolation method is to determine the smoker/never smoker exposure ratio. Ideally, the exposure ratio is based on carcinogenically equivalent exposures, such that one unit of exposure for a never smoker has the same lung cancer risk as one unit of exposure for an active smoker. However, no carcinogenically equivalent measure of exposure exists because smokers and never smokers inhale different types of tobacco smoke. Smokers mostly inhale mainstream smoke produced at temperatures above 600°C and then drawn through the cigarette and filter, whereas the ETS inhaled by never smokers consists mostly of sidestream smoke formed between puffs at 350°C and, partly, of exhaled mainstream smoke. Due to the different combustion temperatures, the amount of specific carcinogens in mainstream and sidestream smoke differs. For example, measurements of two brands of modern filter cigarettes find that fresh sidestream smoke contains 42 times more N-nitrosodimethylamine and 1.5 times more benzo(a)pyrene, but 15% less catechol (a major cocarcinogen (Hecht *et al.*, 1981)) and 70% less N-nitrosonornicotine, by weight, than mainstream smoke (Adams *et al.*, 1985). The problem of the relative carcinogenicity of mainstream and sidestream smoke is exacerbated by the possibility of substantial differences in the composition of their gaseous and particulate phases; however, this has not been studied adequately. Overall, the relative carcinogenicity per unit weight of mainstream and sidestream smoke is not known, though there is some evidence to indicate that particulate sidestream smoke is more carcinogenic than mainstream smoke. An animal study cited by Wynder and Hoffman (1967) finds more skin cancers among shaved mice painted with particulate sidestream versus mainstream condensates. A series of four Ames mutagenicity assays finds particulate sidestream smoke to be over ten times more mutagenic than an equivalent amount, by weight, of mainstream smoke in one test series, though there is little difference in the other three tests (Lofroth & Lazaridis, 1986).

In the absence of a measure of the carcinogenicity of mainstream and sidestream smoke, this study uses the current and never smoker's retained exposure to particulate ETS to estimate the smoker/never smoker exposure ratio. The exposure estimate adjusts for the dilution of sidestream smoke by ambient air. As a first approximation, the carcinogenicity of mainstream and sidestream particles is assumed to be equal (the effect of assuming a greater carcinogenicity for sidestream smoke is discussed later). Exposure to the gas phase of mainstream and sidestream smoke is not included because exposure to the gas phase, without concurrent exposure to tobacco smoke particulates, has not been found to cause lung cancer (Hoffmann *et al.*, 1978; SG, 1982). However, it is possible that future research may establish a significant carcinogenic role for the gas phase.

The smoker/never smoker exposure ratio is also based on the retained exposure (the amount of particulate by weight deposited in the lungs) instead of the inhaled exposure. A significant proportion of the latter is immediately exhaled and, consequently, has no effect on carcinogenesis. Hiller *et al.* (1982) experimentally determine in 11% particulate retention rate for never smokers exposed to sidestream smoke. Similar results have been found for other particulates in the size range of sidestream smoke (Davies *et al.*, 1972; Heyder, 1982). Conversely, the average active smoker retains between 47% and 96% of inhaled mainstream smoke, with most estimates falling above 70% (Dalhamm, 1968; Hoegg, 1972; Corn, 1974; First, 1984). The higher deposition rate for active smokers is thought to result either from deeper inhalation (Muir, 1974), hygroscopic growth and coagulation (Hiller *et al.*, 1982), or from electrical charges in mainstream smoke (Stober, 1984).

ETS exposure and cotinine. Tobacco smoke exposure can also be determined from blood, urine or saliva levels of cotinine — a nicotine metabolite. Cotinine appears, at first, to be a more accurate measure of exposure than retained particles. The latter can only be indirectly estimated for never smokers from exposure to all respirable particles, which include dust, pollen, and other aerosols. In contrast, cotinine is an accurate and specific indicator of tobacco smoke exposure because it is the only important source of exposure to nicotine. Cotinine also measures dose (the amount of a tobacco constituent metabolized by the body), whereas an estimate of retained particles only measures exposure. Unfortunately, though several studies show that cotinine levels in body fluids can accurately differentiate between never smokers with high, moderate and low ETS exposure (Jarvis *et al.*, 1984; 1985) or between nonsmokers and current smokers (Wald *et al.*, 1984), cotinine levels in never and current smokers are not directly comparable. This is

Table 1. Estimated number of never, ex-, and current smokers ≥ age 35 in 1980 in the U.S.*

	Men		Women		
Smoking Status	Number	Percent	Number	Percent	Total
Never	11,960,000	27.03	28,846,000	55.66	40,806,000
Ex-	15,314,000	34.62	7,774,000	15.00	23,088,000
Current	16,965,000	38.35	15,201,000	29.34	32,166,000
Total	44,239,000	100.00	51,821,000	100.00	

*Based on U.S. Census figures for the total male and female population ≥ 35 years of age (USDC, 1982) and the percentage of never smokers, ex-smokers and current smokers of all races ≥ 35 from the 1979/1980 National Health Interview Survey.

partly because the half-life of cotinine is substantially shorter for current than never smokers (Kyerematen *et al.*, 1982; Lynch, 1984; Sepkovic *et al.*, 1986), so that cotinine levels could underestimate the relative exposure received by the lungs of smokers. However, the major problem with using cotinine to determine relative exposures is due to the occurrence of nicotine in a protonated form in the particulate phase of the mainstream smoke inhaled by smokers but in an unprotonated form in the gas phase of the sidestream smoke inhaled by nonsmokers (Eudy *et al.*, 1986; IARC, 1985). Consequently, cotinine or nicotine levels in smokers measure the lung's particulate exposure, whereas these levels in nonsmokers largely measure nasal and pharyngeal exposure to gas phase constituents with a similar retention rate to that of nicotine. The two estimates of exposure are not comparable because they differ both by site and type of exposure. Nonsmokers should also absorb a higher percentage of inhaled nicotine than smokers because the unprotonated nicotine of sidestream smoke is absorbed more rapidly than the protonated nicotine of mainstream smoke (IARC, 1985).

Data Sources and Assumptions

Though superficially simple, the calculation of each of the four preliminary estimates is based on a large number of estimated parameters. These parameters are obtained from published data and analyses of the 1970 (NCHS, 1970) and 1979/1980 National Health Interview Surveys (NCHS, 1981). Due to the large sample size of the National Health Interview Surveys (the 1970 and 1979/1980 NHIS contain smoking data for a sample of 74,451 and 37,604 individuals ≥ 17 years of age, respectively), these surveys provide the best available estimates of the number of never, ex-, and current smokers by occupation, age, and sex (Table 1). Studies of ambient particulate ETS levels in white-collar workplaces in the U.S. are identified from the Building Performance Database, an on-line database accessible through national data networks (Sterling *et al.*, 1985). Most of the identified studies were conducted by the National Institute for Occupational Safety and Health.

All four preliminary estimates are based on estimated average exposures and risks for never and current smokers in 1980. The best exposure-based risk estimate would compare cumulative lifetime exposure for never and ever smokers, because the lifetime exposure of many ex-smokers exceeds that of current smokers. Unfortunately, no cumulative lifetime exposure data for a representative sample of ever and never smokers exists. The estimated risk and the number of excess lung cancer deaths are given for never smokers age 35 and over because almost all lung cancer deaths occur in this age group. However, the average exposure is calculated for never smokers ≥ 17 years of age. ETS exposure is more frequent among young adults (Friedman *et al.*, 1983), and this early exposure could latently affect the lung cancer risk.

In addition to many minor assumptions concerning the accuracy and representativeness of the data, the final estimate of the number of never smoker lung cancer deaths from exposure to particulate ETS is based on four major assumptions:

1. The carcinogenicity of tobacco smoke depends upon exposure to the particulate phase,
2. The lung cancer risk per unit exposure to mainstream and sidestream particulate tobacco smoke is the same,
3. The relationship between risk and each unit of exposure is approximately linear, and
4. There is no low exposure threshold where the lung cancer risk falls to zero.

Calculation of the Linear Extrapolation Estimate

The following three sections calculate the average particulate ETS exposure for never smokers and current smokers as well as the lung cancer risk for current smokers. The population of never smokers, estimated from the 1979/1980 National Health Interview Survey, is given in Table 1.

Never Smoker's Average Particulate ETS Exposure

Almost all particulate ETS exposure occurs indoors

Table 2. Estimated time budgets (hours/day)[a] in 1980 in the U.S.

Location	Employed Women	Employed Men	Housewives	All Women	All Men
In homes (their own and others)	16.3	14.1	21.3	18.6	15.7
Workplace	4.7	6.1	0.0	—	—
Places of business and other locations	1.3	1.4	1.5	1.5	1.3
Restaurants and bars	0.3	0.5	0.1	0.2	0.4
Outside of homes and in transit	1.4	1.9	1.1	—[b]	—
	24.0	24.0	24.0		

[a]The 1965 data from Szalai (1972) are adjusted to account for a 9% drop in the average hours worked between 1965 and 1980 (USDC, 1981). The reduction in work time, 0.6 hours for men and 0.5 hours for women, is divided among the time spent in the four other locations.
[b]No exposure is assumed for this category.

because of low indoor ventilation rates and because adults spend over 85% of their time indoors (Szalai, 1972). The average never smoker's exposure to particulate ETS depends on 1) the average inhalation rate and, for each indoor location, 2) the time spent there, 3) the average particulate ETS level, and 4) the proportion of never smokers exposed.

1. Inhalation rate

Data from Altman and Ditmer (1971) indicate an average inhalation volume of 1.08 m^3/hour for men and 0.62 m^3/hour for women, based on the average volume of air inhaled at rest and during light work.

2. Time spent in five locations

The results of a 1965 44-city time budget study (Szalai, 1972) are used to estimate the average daily time spent by never smokers in five locations; home, work (including time before and after work and during lunch), places of business and other locations, restaurants and bars, and outside the home and in transit. The time spent in restaurants and bars is determined separately, because they sometimes have very high ambient particulate ETS levels. Unfortunately, the original data do not permit dividing time into indoor and outdoor hours — time spent in both "places of business and other locations" and "outside of home and in transit" includes indoor and outdoor locations. To simplify matters, we assume that all time spent in "places of business and other locations" is indoor time where particulate ETS exposure occurs and all time spent "outside of home and in transit" is outdoor time with no particulate ETS exposure.

Table 2 estimates the average time spent in each location by employed men, employed women, and housewives. The time budget for housewives is used to estimate the time budget for all nonemployed men and women ("nonemployed" includes individuals actively seeking work, homemakers, and retirees). Time spent in nonwork locations is adjusted for the proportion of nonemployed adults because, according to time budget results, housewives spend more time in places of business and less time in restaurants and bars than do employed individuals. The 1979/1980 National Health Interview Survey estimates that 19.1% of male and 49.2% of female never smokers are nonemployed. Table 2 also gives the employment-weighted time spent in each nonwork location.

3. Indoor particulate ETS levels

Indoor particulate ETS exposure is indirectly estimated from on-site measurements of total or respirable suspended particles. This method requires an adjustment for background (nonsmoking-related) particulate levels. Background measurements should be taken indoors when no one has smoked for several hours but when all other conditions are the same as during periods of smoking (these criteria are rarely met). If there are no indoor background measurements, outdoor measurements are used as a crude estimate of the indoor particulate level in the absence of smoking.

Estimated particulate ETS levels in restaurants and bars. The average particulate level (unadjusted for background levels) in 27 restaurants, bars and entertainment facilities is 0.30 mg/m^3 (see Table 3). The average indoor particulate ETS level, after adjusting for the average background particulate level of 0.04 mg/m^3, is 0.26 mg/m^3.

Estimated particulate ETS levels in places of business. The estimated average particulate ETS level in offices (see below) is also used for the time budget category "places of business and other locations" (banks, shopping centers, etc.).

Estimated particulate ETS levels in the workplace. Workplace particulate levels are available for restaurants, bars, offices, and service buildings. It is impossible to estimate particulate ETS exposures from particulate levels in indoor blue-collar workplaces because of high background particulate levels from industrial activities. The average particulate ETS exposure should be less for blue-collar than white-collar never smokers because blue-collar workplaces, compared to offices, are better ventilated in order to re-

Table 3. Particulate levels (mg/m³) in bars, restaurants and entertainment facilities in the U.S.

Reference	Premise	Measurement Type	#	Mean	Background (# measurements)
Cuddeback *et al.*, 1976	2 Taverns	TPM[a]	5	0.445	(none)
Elliot & Rowe, 1975	3 Arenas	TPM	19	0.367	0.07 (2 indoors)
First, 1984	3 Taverns	nd[b]	nd	0.543	(none)
	3 Restaurants	nd	nd	0.220	(none)
Repace & Lowrey, 1980	17 Entertainment facilities[c]	RSP[d]	20	0.243	0.04 (4 indoors)
			Average:[e]	0.30	
		Adjusted for background levels:[f]		0.26	

[a]Total particulate matter.
[b]No data given.
[c]Three bars, seven restaurants, and one each of a lodge, bar and grill, firehouse bingo game, church bingo game, inn, bowling alley, and an arena. Active smoking occurred during the time of all measurements.
[d]Respirable suspended particles.
[e]The average is determined by weighting for the number of premises in each study.
[f]Adjusted for Repace and Lowrey's (1980) background level of 0.04 mg/m³. The background level of Elliot and Rowe is not used because it is for arenas which make up only a small proportion of high exposure workplaces.

duce dust and fume exposure and because smoking is prohibited in a higher percentage of blue-collar workplaces (NICSH, 1978). However, we assume that exposed blue-collar workers receive the same particulate ETS exposure as white-collar office workers.

Table 4 summarizes the results of twenty studies of particulate levels in office or service buildings in the U.S. The mean total and respirable particulate levels are 0.08 mg/m³ and 0.068 mg/m³, respectively. The overall mean particulate level, ignoring the difference between total and respirable particulates, is 0.076 mg/m³. The mean level, limited to twelve studies where active smoking was reported to occur during the time of measurement, is also 0.076 mg/m³.

Outdoor background levels, reported by seven studies, average 0.053 mg/m³ and range from 0.01 to 0.1 mg/m³. The indoor background level in the absence of active smoking is 0.035 mg/m³ in two studies of offices (Parker *et al.*, 1983; Collett, 1985) and 0.037 mg/m³ in one study of an office and two libraries (Repace and Lowrey, 1980).

The minimum background outdoor particulate level of 0.01 mg/m³ is used to conservatively estimate the indoor particulate ETS level because indoor particulate levels for 13 studies are below the outdoor average of 0.053 mg/m³ while in eight studies the indoor particulate level is below the indoor background level of approximately 0.035 mg/m³. Therefore, up to 0.066 mg/m³ (0.076–0.01) of airborne particles in office and service buildings could be from tobacco smoke, assuming no other indoor sources of particles.

Estimated particulate ETS levels in residences. Five field studies measure the effect of at least one smoker on the 24-hour particulate level in residences. Table 5 shows that one smoker increases the hourly particulate level over background levels (homes with no smokers) by an average of 0.015 mg/m³, while two smokers increase the particulate level by an average of 0.042 mg/m³. The latter average is assumed to represent all residences with two or more smokers.

The average home exposure is weighted by the proportion of never smoking respondents to the 1970 National Health Interview Survey who reported living with one versus two or more smokers. The weighted average hourly particulate ETS level in the residences of never smokers is approximately 0.02 mg/m³ for both sexes.

4. Proportion of never smokers exposed in each location

All never smokers are assumed to be exposed in "restaurants and bars" and "places of business and other locations." The proportion exposed at work is estimated from the occupational distribution of never smokers while the proportion exposed at home is estimated from the proportion of never smokers who report living with a current smoker (spouse, relative, friend, etc.).

Proportion of never smokers exposed at work. Table 6 gives the 1979/1980 National Health Interview Survey employment distribution of never smokers age 17 and older. Occupations are grouped by the likelihood of particulate ETS exposure. Students are categorized as working in indoor white-collar environments, while blue-collar workers are separated into outdoor and indoor workers. All white-collar, indoor blue-collar, and restaurant and bar employees are assumed to be exposed to particulate ETS at work, while nonemployed individuals and outdoor workers are assumed to receive no workplace exposure. In total, 66.7% of all male and 49.3% of all female never smokers are estimated to be exposed to particulate ETS at work.

Proportion of never smokers exposed at home. The

Table 4. Particulate levels (mg/m³) in white-collar workplaces in the U.S.

Reference	Use	Building Smoking[a]	Employees[b]	Measurement Type	#	Length	Date	Mean
Blake *et al.*, 1981	Store	nd	nd	TPM	10	nd	Nov/79	0.019
Chrostek, 1979	Office	nd	30	RSP[c]	1	7 hr	May/79	0.030
Chrostek & Moshell, 1982	Office	nd	100	TPM	5	8 hr	Aug/81	0.120
Collett, 1985	Office	Y	6[d]	RSP	8	40 min	Jul/85	0.050
Cornwell *et al.*, 1981	Office	Y	>100	RSP	28	2 min	Nov/80	0.048
Gorman, 1980	Office	nd	6	TPM	nd	nd	Jul/80	0.11[e]
Gunter & Thoburn, 1985	Office	nd[f]	nd	TPM[g]	7	6.5 hr	Nov/84	0.164
Hicks, 1981a	Office	Y	nd	nd	3	nd	Mar/80	0.047
Hicks, 1981b	Office	nd	40	TPM	2	6 hr	Dec/80	0.055
Hodgson & Morley, 1983	Office	nd	41	RSP	3	nd	Mar/83	0.025
Hollett, 1979	Office	nd	nd	TPM	21	nd	Jul/79	0.143[h]
Moschandreas *et al.*, 1980	Office	Y	150	TPM	3	24 hr	nd	0.030[i]
	Office	Y	100	TPM	3	24 hr	nd	0.038[j]
Neal *et al.*, 1978	Hospital	Y	nd	TPM	41	48/hr	Aug–Feb	0.030
Parker *et al.*, 1983	Office	Y	100	TPM	2	8 hr	Feb/83	0.032
	Office	Y	16	TPM	3	8 hr	Feb/83	0.094
Repace & Lowrey, 1980	Hospital waiting room	Y	nd	RSP	1	12 min	Mar	0.187
Salisbury, 1979	Stock Exchange	Y	nd	TPM	3	5 hr	Oct/78	0.287
Salisbury *et al.*, 1982	Office	Y	500	TPM	8	6 hr	Mar/81	0.038
Tharr, 1980	Office	nd	100	TPM	2	7 hr	Jun/80	0.060
Thompson *et al.*, 1973	2 stores	nd	nd	TPM	nd	nd	Nov/71	0.083
Turiel *et al.*, 1981	Office	Y	nd	TPM	nd	12 hr	nd	0.031
							Average:	0.076
			Adjusted for Background Level (see text):					0.066

[a]Active smoking while particulate levels were sampled.
[b]On the floor(s) where measurements taken.
[c]Respirable suspended particles.
[d]In immediate area of sampler, two of the six staff were smokers.
[e]Close to office copier.
[f]No data given.
[g]Total particulate matter.
[h]Major construction site across the street.
[i]Based on 24 hour sample. Maximum recorded 0.057 mg/m³.
[j]Based on 24 hour sample. Maximum recorded 0.130 mg/m³.

Table 5. Effect of smoking on 24-hour respirable suspended particle (RSP) levels (mg/m³) in residences in the U.S.

Reference	Mean RSP Level in Homes with No Smokers	1 Smoker	2 Smokers	Increase due to 1 Smoker	2 Smokers
Spengler *et al.*, 1981	0.024	0.037	0.052	0.012	0.027
EPRI, 1984	0.024	0.043	0.075	0.019	0.051
Hosein & Corey, 1986[a]	0.038	0.053	0.080	0.015	0.042
Lebowitz *et al.*, 1984	0.018	0.033[b]	—	0.015	—
Spengler *et al.*, 1985	0.028	—	0.074[b]	—	0.046
			Average:	0.015	0.042

[a]Average of reported winter and summer means.
[b]Number of resident smokers not given in reference. The results have been assigned to the most probable category, on the basis of the results of the other studies.

Table 6. 1979/1980 National Health Interview Survey estimate of the occupational distribution of never smokers ≥ age 17 in the U.S.

Occupation	Men (%)	Women (%)
Indoor white-collar[a]	43.3	41.0
Indoor blue-collar[b]	21.6	6.2
Restaurants and bars[c]	1.8	2.1
Outdoor workers[d]	14.2	1.5
Not employed[e]	19.1	49.2
	100.0	100.0

[a]Includes students and professional, managerial, technical, clerical and service occupations.
[b]Includes industrial and warehousing occupations.
[c]Includes waiters and waitresses, entertainers, bartenders, busboys, recreation and amusement attendants, pub and food service workers.
[d]Includes construction, agriculture, forestry and fishing occupations.
[e]Includes retired, homemakers and unemployed.

1970 National Health Interview Survey estimates that 29.6% of male and 35.7% of female never smokers age 17 and over live with a current smoker. Since the 1979/1980 National Health Interview Survey does not include smoking information for all household members, it cannot be used for this purpose. However, using data for 1970 should overestimate the proportion of never smokers exposed at home in 1980 because the number of active smokers has declined 6% for men and 2% for women between 1970 and 1980 (Weinkam & Sterling, 1987).

Estimated particulate ETS exposure

Table 7 summarizes the average never smoker's inhalation exposure to particulate ETS. The average daily inhaled particulate ETS exposure is 0.62 mg for male and 0.28 mg for female never smokers. The daily retained particulate ETS exposure, based on an 11% retention rate, is 0.07 mg for male and 0.03 mg for female never smokers.

Current Smoker's Average Exposure

The average smoker's daily exposure to particulate tobacco smoke is assumed to equal the average number of cigarettes per day consumed multiplied by the average tar delivery per cigarette. For simplicity, the current smoker's particulate ETS exposure is not included because it is only a small fraction of the current smoker's total particulate tobacco smoke exposure. An average consumption of 29.3 cigarettes per day for current smokers is calculated by dividing the 1979/1980 average of 626.5 billion cigarettes sold in the U.S. (Maxwell, 1981) by the 1979/1980 National Health Interview Survey estimate of 58.5 million current smokers age 17 and over. The average of 29.3 cigarettes per day is used for both sexes because there is little difference in the 1979/1980 National Health

Table 7. Estimate of the average never smoker's inhalation exposure of particulate environmental tobacco smoke (ETS) (mg/day) in 1980 in the U.S.

Location	Respiration Rate/hour	Ambient ETS mg/m³	Hours of Exposure	Proportion Exposed	Weighted Exposure
Men					
Home	1.08	0.02	15.7	0.296	0.100
Rest/Bar[a]	1.08	0.26	0.4	1.000	0.112
Other[b]	1.08	0.066	1.3	1.000	0.093
Work					
White-collar	1.08	0.066	6.1	0.433	0.188
Blue-collar	1.08	0.066	6.1	0.216	0.094
Rest/Bar	1.08	0.26	6.1	0.018	0.031
No Workplace Exposure[c]	—	—	—	0.333	0.000
					Total 0.62
Women					
Home	0.62	0.02	18.6	0.357	0.082
Rest/Bar	0.62	0.26	0.2	1.000	0.032
Other	0.62	0.066	1.5	1.000	0.061
Work					
White-collar	0.62	0.066	4.7	0.410	0.079
Blue-collar	0.62	0.066	4.7	0.062	0.012
Rest/Bar	0.62	0.27	4.7	0.021	0.016
No Workplace Exposure	—	—	—	0.501	0.000
					Total 0.28

[a]Restaurants and bars.
[b]Places of business and other locations.
[c]Unemployed, retired, homemakers, and outdoor workers.

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Table 8. National Mortality Followback Survey estimate of the number of lung cancer deaths (LCD) among never smokers in the U.S. in 1980

Age	LCD/100,000[a]	Never Smokers (100,000)[b]	Estimated LCD
Men			
35–44	2.3	37.08	85.3
45–54	3.5	25.68	89.9
55–64	33.4	22.91	765.2
65–74	63.8	19.80	1,263.2
75–84	87.9	11.05	971.3
85+	100.0[c]	3.04	304.0
			Total: 3,479
Women			
35–44	0.4	62.60	25.0
45–54	2.8	61.30	171.6
55–64	10.9	61.30	668.2
65–74	18.7	55.96	1,046.5
75–84	48.4	36.87	1,784.5
85+	60.0[c]	10.27	616.2
			Total: 4,312

[a]From Enstrom & Godley (1980).
[b]Estimated from the 1979/1980 National Health Interview Survey age distribution of never smokers of all races and the U.S. Census (USDC, 1982) estimate of the population in 1980.
[c]Estimated from the American Cancer Society study (Garfinkel, 1981) as the rates for this age group were not given by the National Mortality Followback Survey (Enstrom & Godley, 1980). The American Cancer Society never smoker lung cancer rates are 94.8 for men and 52.4 for women 85–89 years of age. These rates are increased slightly to account for higher rates among people older than 89 and for the higher incidence of occupational exposures for the entire U.S. population.

Interview Survey estimate of the average consumption by sex; the average female smoker consumes 96% of the average for male smokers.

The 1980 sales-weighted average tar delivery per cigarette, excluding particulate nicotine, is 13.2 mg/day (Tobacco Institute, 1981). This average is used in the risk estimates for men. However, data from the American Cancer Society study show that women inhale approximately 20% less than men (Hammond, 1966). We assume that women in 1980 still inhale 20% less than men, and are thus exposed to 10.6 mg/day. The average daily particulate tobacco smoke exposure is, consequently, 387 mg for male and 311 mg for female smokers. The daily retained exposure, based on an 80% retention rate, is 310 mg for male and 249 mg for female smokers, excluding exposure to ETS.

Current Smoker's Average Lung Cancer Rate

In 1980 there were 75,362 male and 28,210 female lung cancer deaths among individuals age 35 and over (NCHS, 1986). The number of lung cancer deaths among current smokers cannot be directly determined because the smoking status of decedents is not noted on death certificates. The number of current smoker lung cancer deaths from tobacco smoke exposure is obtained by subtracting, from the total number of lung cancer deaths, an estimate of the number of lung cancer deaths among never smokers, ex-smokers, and current smokers due to nonsmoking causes.

Lung cancer deaths among never smokers

Age-specific lung cancer death rates are available for white never smokers from the National Mortality Followback Survey (Enstrom & Godley, 1980). The use of these rates assumes indentical rates for nonwhites and no change in the lung cancer death rate for never smokers between 1966–1968 and 1980. These lung cancer death rates, multiplied by the age-specific number of never smokers in 1980, estimate 3,479 male and 4,312 female never smoker lung cancer deaths in the U.S. in 1980 (Table 8).

Lung cancer deaths among ex-smokers

The number of lung cancer deaths among the 23.09 million ex-smokers in 1980 is estimated from the average lung cancer relative risk for current versus ex-smokers in two cohort studies: the American Cancer Society study (Hammond, 1964) and the U.S. Veterans study (Rogot & Murray, 1980). The male risk ratios are also used for women because none of the cohort studies reports the risk for all ex- and current female smokers.

The average lung cancer risk for all current versus all ex-smokers is 2.26, based on a risk of 1.67 in the American Cancer Society study and 2.85 in the Veterans study. The average ratio of 2.26, combined with the 1979/1980 National Health Interview Survey estimates of the number of current and ex-smokers, predicts 20,517 male and 4,410 female ex-smoker lung cancer deaths.

The difference in the risks for ex-smokers compared to current smokers in the two studies is probably due to the higher percentage of long-term ex-smokers, with lower lung cancer rates than short-term ex-smokers, in the Veterans study. All ex-smokers in the Veterans study had not smoked for a minimum of twelve years compared to a minimum of 34 months for ex-smokers in the American Cancer Society study. The American Cancer Society results may be more appropriate here because the National Health Interview Survey estimate of the number of ex-smokers includes both short and long-term ex-smokers.

Current smoker lung cancer deaths not attributable to smoking

The number of nonsmoking-attributable current smoker lung cancer deaths is estimated by assuming that smokers would experience the mortality rates of the National Morality Followback Survey never smokers if they did not smoke. These mortality rates, applied to the 1979/1980 National Health Interview Survey estimate of the sex and age-specific population of current smokers, estimate 3,111 male and 1,094 female lung cancer deaths.

Smoking attributable lung cancer risk for current smokers

The number of smoking-attributable lung cancer deaths among male current smokers over 35 is 48,255, obtained from subtracting 3,479 never smoker, 20,517 ex-smoker, and 3,111 nonsmoking-attributable lung cancer deaths among current smokers from the 1980 total of 75,362 male lung cancer deaths. The same method estimates 18,394 smoking-attributable lung cancer deaths among female current smokers over 35 in 1980. Given 16.965 million male and 15.201 million female current smokers over 35 in 1980, this estimates a smoking-attributable lung cancer risk of 284 lung cancer deaths (LCD)/100,000 male and 121 LCD/100,000 female current smokers over age 35. Repace and Lowrey (1985) estimate a rate of 316 LCD/100,000 male or female smokers for use in their linear extrapolation estimate. However, they assume that all smoking-attributable lung cancer deaths occur among current smokers only (no deaths among ex-smokers), they do not adjust for occupational or other causes of lung cancer among smokers, and they include cancers of the larynx and other non-lung sites.

Lung Cancer Risk for Never Smokers From Particulate ETS Exposure

The estimated daily retained exposure is 310 mg for male and 249 mg for female current smokers and 0.07 mg for male and 0.03 mg for female never smokers. The male smoker's retained exposure is 4,429 times greater than the average male never smoker's retained exposure. Given a smoking-attributable lung cancer death rate for male current smokers of 284 LCD/100,000, the average male never smoker's lung cancer risk is 0.064 LCD/100,000, which predicts approximately 8 lung cancer deaths from exposure to particulate ETS among the 11.96 million male never smokers in 1980. The same method estimates a risk of 0.015 LCD/100,000 female never smokers, which predicts 4 lung cancer deaths from exposure to particulate ETS among the 28.85 million female never smokers in 1980.

Reliability of the Estimate

The linear extrapolation estimate of 12 never smoker lung cancer deaths in 1980 from exposure to particulate ETS is based on a large number of unverifiable assumptions and parameter estimates. Due to the large number of assumptions, it is neither meaningful nor possible to calculate upper and lower confidence limits. However, the reliability of each of the four preliminary estimates is assessed below. Evidence indicates that several of the preliminary estimates are more likely to result in an overestimate rather than an underestimate of the true number of never smoker lung cancer deaths. However, a plausible upper estimate is calculated for three of the four preliminary estimates. These upper estimates are used to calculate a maximum final estimate, given the major assumptions of the linear extrapolation method.

Number of Never Smokers

The final estimate of the number of never smoker lung cancer deaths increases if the estimated number of never smokers increases. The present estimate of 11.96 million male and 28.85 million female never smokers is based on self-reported smoking status, and is probably an overestimate of the number of never smokers. Two-stage interview studies show that approximately 5% of self-reported never smokers are actually ex- or current smokers (NRC, 1986). For this reason, the estimated number of never smokers is not increased when calculating the upper estimate.

Never Smoker's Average Exposure

The estimated number of never smoker lung cancer deaths increases if the average never smoker's exposure increases. Several factors suggest that our estimated exposure *overestimates* the true exposure. For

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example, many of the measurements of total or respirable particles are for workplaces which probably had higher than average particulate ETS levels. Most buildings in the Building Performance Database were studied in response to occupant complaints about "building illness" or poor indoor air quality. Even though tobacco smoke may not be an important factor in building illness (Sterling *et al.*, 1987), it could affect the occupants' perception of the air quality and lead to more complaints in buildings with high versus low particulate ETS levels. In addition, all indoor blue- and white-collar workers are assumed to be exposed to particulate ETS at work, even though smoking is prohibited in 11% of white- and 28% of blue-collar workplaces (NICSH, 1978). Interview studies also show lower workplace exposure rates than the estimated rate of 66.7% for male and 49.3% for female never smokers. For example, only 29.4% of the control group of female never smokers in a case-control study report workplace exposure during the past 25 years (Garfinkel *et al.*, 1985). In a 1979/1980 questionnaire survey of 37,881 never smokers, only 40.4% of both sexes combined reported ETS exposure in "small spaces" such as at work (Friedman *et al.*, 1983).

Two field studies contain enough information to calculate the average inhaled particulate ETS exposure for men. Both of these studies estimate average particulate ETS exposures that are within six percent of the comparable estimates given in Table 7. The studies use personal monitors, carried by subjects for several days, to determine average exposures to respirable suspended particles. The difference between the average personal and background (outdoor) exposures to respirable suspended particles in a study of 48 subjects, none of whom live with a smoker, is 0.019 mg/m^3 (Sexton *et al.*, 1984). If particulate ETS accounts for all of the difference in respirable suspended particles, then the average 24-hour particulate ETS exposure at a male respiration rate of 1.08 m^3/hour, is 0.49 mg/day. For comparison, our estimate of the average daily inhaled exposure of male never smokers with no home exposure is 0.52 mg/day (see Table 7). Spengler *et al.* (1985) determine personal exposures to respirable suspended particles for 101 volunteers in two industrial towns in Tennessee. The difference between the average personal exposure and the background (outdoor) level is 0.024 mg/m^3. This predicts an average daily particulate ETS exposure of 0.62 mg/day, which is identical to our estimate for men.

Repace and Lowrey (1985) estimate an average inhaled exposure for either sex of 1.43 mg/day, based on modeling indoor smoking, occupancy, and ventilation rates, which is 3.18 times the average of our estimates for men and women. There are several possible causes for the difference. For example, Repace and Lowrey assume that all never smokers are actively employed and, therefore, possibly exposed at work. In contrast, the 1979/1980 National Health Interview Survey estimates that approximately 40% of all never smokers are not employed. Furthermore, Repace and Lowrey calculate the average ambient ETS level in the workplace from the average of modeled levels in low-exposure and high-exposure workplaces. Their model estimates an ambient particulate level (from tobacco smoke alone) of 0.17 mg/m^3 for low-exposure workplaces such as offices and of 0.42 mg/m^3 for high-exposure workplaces. The particulate level for the latter is representative of measured levels in very smoky workplaces such as taverns, bars, and dance halls. The average for the two types of workplaces is 0.30 mg/m^3, which is higher than all of the measured levels for white-collar workplaces (see Table 4) and higher than the average for restaurants, bars and other entertainment facilities (see Table 5). It may not be appropriate to average the estimate for low and high-exposure workplaces, because the 1979/1980 National Health Interview Survey estimates that approximately twenty times as many never smokers work in low-exposure workplaces such as offices than in high-exposure workplaces such as bars and taverns.

There is no plausible average upper estimate for the inhaled exposure which is substantially greater than the estimates given in Table 7, which is also based on field measurements of ambient particulate levels. However, an arbitrary upper estimate can be made by doubling the previous estimates. Thus, the upper inhaled estimates are 1.24 mg/day for male and 0.56 mg/day for female never smokers. These give average retained exposures of 0.14 mg/day for male and 0.06 mg/day for female never smokers.

Current Smoker's Average Exposure

The estimated number of never smoker lung cancer deaths increases if the average smoker's true exposure, derived from the average tar delivery per cigarette multiplied by the average cigarette consumption, is *less* than estimated.

The average tar delivery per cigarette is based on machine smoked deliveries. The machine smoking standard of one two-second 35 ml puff/minute was established over 30 years ago to reflect the smoking habits of that time. Since then, several studies indicate that smokers partially compensate for a decline in the nicotine delivery per cigarette by smoking each cigarette more intensely (Ashton *et al.*, 1979; Herning *et al.*, 1981; Hill & Marquardt, 1980; Russell *et al.*, 1975). This is done by increasing the average puff frequency and/or volume or by inhaling more deeply. The probable increase in the intensity with which cigarettes are smoked indicates that the estimated exposure for current smokers is more likely to *underestimate* than overestimate the true exposure.

Conversely, the average consumption of 29.3 ciga-

rettes per day is based on sales data for the number of cigarettes sold in 1980 divided by the 1979/1980 National Health Interview Survey estimate of the number of current smokers. Estimates based on interviews with current smokers are not used because smokers significantly underreport their cigarette consumption (Todd, 1978). However, the estimate of 29.3 cigarettes per day may be too high because the 1979/1980 National Health Interview Survey excludes smokers under age 17 and because some of the self-reported never and ex-smokers should be current smokers (NRC, 1986). If the probable increase in smoking intensity is ignored, an increase in the estimated number of current smokers by 10% (to account for smokers under age 17 and misclassified never smokers) decreases the average daily retained exposure from 310 mg to 283 mg for male and from 249 to 228 mg for female current smokers. This is further decreased to 166 mg for male current smokers and to 134 mg for female current smokers by using the lowest experimentally determined particulate retention rate of 47% (First, 1984) instead of an 80% retention rate.

Current Smoker's Average Lung Cancer Rate

The estimated number of never smoker lung cancer deaths increases if the lung cancer risk for current smokers increases. This occurs if the estimated number of lung cancer deaths decreases among (1) ex-smokers, (2) never smokers, and (3) current smokers who die from causes other than smoking. This is calculated for the latter two groups by using the American Cancer Society never smoker lung cancer death rates (Garfinkel, 1981) instead of the rates from the National Mortality Followback Survey. The American Cancer Society rates were not used before because they are for an unrepresentative group of mostly middle-class individuals (Hammond & Seidman, 1980), whereas the National Mortality Followback Survey rates are based on a representative sample of all never smoker lung cancer deaths. The number of ex-smoker lung cancer deaths is minimized if the ex-smoker/smoker mortality ratio from the Veterans study (Rogot & Murray, 1980) is used instead of the average for the American Cancer Society and Veterans studies combined.

These three changes increase the estimated number of current smoker lung cancer deaths from 48,255 to 55,902 male deaths and from 18,394 to 19,954 female deaths. However, this only slightly alters the lung cancer risk because the revised estimate of the average smoker's exposure depends upon increasing the number of smokers by 10%. Given a 10% increase in smokers, the lung cancer rate increases 5.6% to 300 LCD/100,000 male never smokers, but falls 1.7% to 119 LCD/100,000 female never smokers.

The lung cancer death rate for female current smokers is substantially less than the rate for male current smokers. The difference could partly be caused by women inhaling less deeply than men or by smoking lower tar cigarettes. Alternatively, the lower mortality rate for women could reflect a shorter latency period because women, on average, took up smoking at a later date than men. An upper estimate of the lung cancer death rate for female smokers can be adjusted for this by assuming that the risk/mg of exposure for women is equal to the risk/mg of exposure for men. This estimates a risk of 242 LCD/100,000 female smokers.

Upper Risk Estimate

The upper estimate is 62 lung cancer deaths among never smokers as a result of exposure to particulate ETS. This is based on a lung cancer death rate of 300 LCD/100,000 male and 242 LCD/100,000 female current smokers, an average retained exposure of 166 mg/day for male and 134 mg/day for female current smokers, and a retained exposure of 0.14 mg/day for male and 0.06 mg/day for female never smokers.

Comparison with Other Estimates

The linear extrapolation estimate of 12 deaths, or the upper linear extrapolation estimate of 62 never smoker lung cancer deaths, is substantially less than five alternative estimates, ranging from 265 to 3,610 lung cancer deaths, given in Table 9. All of the alternative estimates use the National Health Interview Survey estimate of the number of never smokers $\geq$ 35 years of age. Three of the alternatives are risk-based estimates derived from the results of epidemiological studies: one from the difference in lung cancer mortality rates between Seventh-Day-Adventists and other never smokers (termed a phenomenological estimate by the authors), and the other two apply average geometric mean lung cancer risks observed in epidemiological studies to the population-attributable risk equation (Cole & MacMahon, 1971). The two remaining estimates are exposure-based estimates derived from smoker/never smoker exposure ratios and linear extrapolation.

To a certain extent, differences among the various estimates are expected because each type of estimate (for example, linear extrapolation or population-attributable risk methods) requires different assumptions and all estimates are only crude approximations without confidence limits. However, even if the confidence limits for all estimates include all other estimates, this does not explain the 22- to 301-fold difference between the linear extrapolation estimate of 12 lung cancer deaths and the other estimates.

The previous discussion shows that the substantial difference between our estimates and the alternative estimates cannot be adequately explained by errors in our estimates of the number of never smokers, the average exposure for current and never smokers, or

Table 9. Alternative estimates of the number of ETS-attributable never smoker lung cancer deaths (LCD) (both sexes combined) in 1980 in the U.S.

Method	Description	Estimated LCDs
Phenomenological	Repace and Lowrey's (1985) sex and age-specific difference in LCD rates between Seventh-Day-Adventist (SDA) and non-SDA never smokers is applied to the 1979/1980 National Health Interview Survey estimate of the U.S. population of never smokers by sex and age (Arundel *et al.*, 1986).	3,610
Linear Extrapolation Based on ETS Exposure	Repace and Lowrey's (1985) estimate of 555 nonsmoker (never and ex-smokers combined) LCDs is adjusted for the National Health Interview Survey estimate of the percentage (63.87%) of nonsmokers that are never smokers.	354
Linear Extrapolation Based on Cotinine Ratios	The estimated smoking-attributable LCD rate for current smokers of 284 LCD/100,000 men and 121 LCD/100,000 women is divided by the ratio of the weighted average urine cotinine level of 1483.7 ng/ml for smokers and 5.72 ng/ml for never smokers in four studies (Williams *et al.*, 1979; Kyerematen *et al.*, 1982; Jarvis *et al.*, 1984; Wald *et al.*, 1984).	265
Population Attributable Risk (PAR) Estimates*		
RR is 1.35	*RR* is Wald's *et al.*, (1986) estimate of the geometric mean risk observed in 13 epidemiological studies from six countries. The risk is 1.53 for never smokers living with smokers and 1.18 for never smokers not living with smokers, after adjustment for the misclassification of 7% of ever smokers as never smokers and a relative difference in ETS exposure of 3.0 (Wald & Ritchie, 1984) for the two groups of never smokers. *p* is 0.249 for male and 0.505 for female never smokers (see text). The average PAR is 0.21 for male and 0.26 for female never smokers.	1,852
RR is 1.14	*RR* is the geometric mean risk observed in 5 epidemiological studies from the U.S. only (NRC, 1986). The risk is 1.16 for never smokers living with a smoker and 1.05 for never smokers living with never smokers after adjustment for a misclassification rate of 6%, a risk for misclassified ever smokers of 2.0 and a threefold exposure difference for the two groups of never smokers. *p* is 0.249 for male and 0.505 for female never smokers. The average PAR is 0.072 for male and 0.094 for female never smokers.	655

*The adjusted PAR equation (Eq. 5, p. 292, NRC, 1986) equals:

$$\frac{p_1(RR_1-1)+(1-p_1)(RR_2-1)}{p_1(RR_1)+(1-p_1)(RR_2)}$$

where p_1 is the proportion of never smokers who live with an ever smoker, RR_1 is the risk for never smokers who live with an ever smoker and RR_2 is the risk for never smokers who live with never smokers. The PAR × *N*, the total number of never smoker LCDs in 1980 (3,479 male, 4,312 female (Table 8)), gives the estimated number of never smoker lung cancer deaths from ETS exposure. The estimates are calculated for each sex and then summed.

the lung cancer risk for current smokers. On the contrary, there is also evidence to indicate that the estimate of 12 lung cancer deaths is too high. The difference cannot be due to an error in the estimated number of never smokers because all estimates are based on the National Health Interview Survey estimate of the population of never smokers ≥ 35 years of age. There are two possible explanations for the difference: either the alternative estimates given in Table 9 overestimate the true risk, or there are major problems with one or more of the four major assumptions underlying the linear extrapolation estimate, which causes it to underestimate the true risk.

Alternative Estimates

Several features of the two alternative linear estimates indicate that they could overestimate the true risk. The estimate based on cotinine ratios assumes that cotinine levels in the blood or urine of smokers

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and nonsmokers measure comparable exposures. As discussed earlier, this assumption is probably not valid. Cotinine in smokers measures the lung's exposure to particulate tobacco smoke, whereas cotinine in nonsmokers measures nasal and pharyngeal exposure to the gas phase. Neither the site nor type of exposure is comparable. Repace and Lowrey's (1985) linear extrapolation estimate could also overestimate the true risk from ETS exposure because it appears to overestimate both the never smoker's average exposure and the average smoker's lung cancer risk. The method also uses the inhaled exposure instead of the retained exposure.

The alternative risk-based estimates depend on epidemiological estimates of the lung cancer risk from ETS exposure. The phenomenological estimate is based on a risk of 1.73 for male and 2.54 for female never smokers, calculated from the difference in lung cancer mortality rates for Seventh-Day-Adventist nonsmokers and another group of nonsmokers. The method assumes that the Seventh-Day-Adventists received less exposure to ETS than the other group of nonsmokers. However, the mortality rates for the Seventh-Day-Adventists are based on only 15 female and 10 male deaths. Consequently, these rates are unstable, with large fluctuations in the death rates instead of a consistent increase with each successive age group. These fluctuations could lead to an overestimate of the lung cancer risk from ETS exposure (Arundel *et al.*, 1986).

The population-attributable risk estimates are based on only three parameters: the geometric mean lung cancer risk from ETS exposure, the proportion of never smokers exposed to ETS, and the number of never smokers at risk. The difference between the population-attributable risk and linear estimates cannot be attributed to errors in the estimated value of the number of never smokers at risk because this parameter is also used in the linear estimate. Both methods also assume that all never smokers are exposed to ETS, though the population-attributable risk method calculates separate risks for the proportion of never smokers exposed to ETS at home and the proportion not exposed at home. These proportions are derived from the 1970 National Health Interview Survey estimate that 24.9% of male and 50.5% of female never smokers age 35 and over live with a current or former smoker.

The population-attributable risk method, based on a geometric mean risk of 1.35 from 13 epidemiological studies, estimates 1,852 lung cancer deaths in 1980 among never smokers from exposure to ETS. The method is similar to that used by Robins (1986). Robins' method estimates 1,807 lung cancer deaths in 1980 among never smokers of both sexes from ETS exposure.

The difference in the linear and population-attributable risk estimates could occur if all estimates of the geometric mean risk overestimate the true risk. Lee (1986) has shown that the misclassification of ever smokers as never smokers could result in an overestimate of the geometric mean risk. However, the population-attributable risk estimates are adjusted for misclassification, though the misclassification rate and the lung cancer risk for misclassified ever smokers is only crudely estimated. The geometric mean risk could also be biased by response or recall bias in the case-control studies on which it is based or by differences in the age distribution of lung cancer cases in the epidemiological studies and the age distribution of never smokers in the U.S. Furthermore, the geometric mean risk is a crude risk; it is not adjusted for age or any other possible or established risk factor for lung cancer such as occupation, socioeconomic status, or diet. The lack of adjustment for other risk factors could bias the geometric mean risk either upwards or downwards.

Assumptions of the Linear Estimate

Three of the four major assumptions of the linear extrapolation estimate can provide a plausible explanation of the difference between our estimate and the population-attributable risk estimates. The assumption of no low threshold, where the risk falls to zero, is irrelevant. The second assumption is that the dose-response relationship is linear. The difference between the estimates can be explained if the true dose-response relationship is nonlinear and convex, such that one unit of exposure at low doses is substantially more carcinogenic than one unit of exposure at high doses. However, most dose-response studies of chemical carcinogens have found sublinear or "hockey stick" shaped relationships between exposure and risk in which one unit of exposure at low doses results in a smaller increase in risk than one unit of exposure at high doses (Hoel *et al.*, 1983). The linear assumption is usually recommended as a conservative estimate of risk because it is believed to err towards overestimating the true risk (Anderson, 1983).

The best fitting equation for the lung cancer death rate per unit of exposure in a 1951–1971 cohort study of 34,440 British doctors is nonlinear and equal to 0.26 $(\text{dose}+6)^2$, where dose is the average number of British cigarettes smoked at the time of the study (Doll & Peto, 1978). This equation indicates that the linear assumption overestimates the risk from ETS exposure. For example, the sales-weighted average British cigarette between 1951 and 1971 delivered 29.9 mg of particulate tobacco smoke to the smoker (Wald *et al.*, 1981). An average inhaled exposure for male never smokers of 0.62 mg/day of particulate ETS (equivalent to 0.02 British cigarettes) results in an annual excess inhaled-exposure risk of 0.06 LCD/100,000 never

Table 10. Relative particulate tobacco smoke exposure for current and never smokers in 1955, 1968 and 1980

	1955	1968	1980
Proportion of population that smoke[a]	0.376	0.386	0.345
Tobacco weight of an average cigarette (grams)[b]	1.12	0.95	0.80
Tar (including nicotine) delivery per cigarette (mg)[c]	40.1	23.1	14.2
Cigarettes/day (CPD) smoked by the average smoker[d]	26.2	29.7	29.3
Never smoker's exposure index[e]	11.0	10.9	8.1
Smoker's daily exposure (mg)[f]	1050.6	686.1	416.1
Ratio of smoker's exposure/never smoker's exposure index	95.5	62.9	51.4

[a]1955: ≥ age 18 (SG, 1979), 1968: ≥ 17 (SG, 1979), 1980: ≥ 17 (1979/1980 National Health Interview Survey).
[b](USDA, 1985).
[c]1955 and 1968 (SG, 1981), 1980 (Tobacco Inst., 1981).
[d]For 1955 and 1968, equals per capita (≥ 18) number of cigarettes sold (Table 1-1, NRC, 1986)/proportion of population who smoke/365. For 1980, equals the number of cigarettes sold/National Health Interview Survey estimate of the number of never smokers ≥ 17.
[e]Proportion of population that smoke × tobacco weight × CPD per smoker.
[f]Tar delivery per cigarette × CPD.

smokers. Adjusting for the retained exposure decreases the risk to 0.008 LCD/100,000, which predicts 1.4 lung cancer deaths among male never smokers compared to the linear estimate of 8 deaths. The same relative decline for female never smokers would estimate 0.9 female lung cancer deaths, for a combined minimum estimate of 2.3 lung cancer deaths in 1980.

The other two assumptions of the linear estimate (equal risk per unit of exposure for smokers and never smokers, and that all risk is attributable to particulate exposure) can be examined together. The difference between our estimate and the population-attributable risk estimates can be explained if ETS is substantially more carcinogenic per unit of exposure than mainstream smoke. The lowest alternative estimate of 265 lung cancer deaths requires ETS to be as much as 22 times more carcinogenic than mainstream smoke, the highest population-attributable risk estimate of 1,852 lung cancer deaths requires ETS to be as much as 154 times more carcinogenic, and the phenomenological estimate requires ETS to be as much as 301 times more carcinogenic. ETS could be more carcinogenic than mainstream smoke if there were substantial differences in the chemical composition, deposition pattern, or deposition site of passively inhaled sidestream smoke versus actively inhaled mainstream smoke.

The linear estimate is essentially based on a difference in exposure between never and current smokers, while the phenomenological and population-attributable risk estimates are based on a difference in risk between never smokers with and without regular exposure to ETS. Given the large difference in the exposure of never and current smokers, the relative risks of 2.54 and 1.73, on which the phenomenological model is based, or the relative risks of 1.34 or 1.14 used in the population-attributable risk estimates, are far too high. In our opinion, a substantially greater carcinogenicity for ETS versus mainstream smoke is the most plausible factor which could explain the large difference between our linear estimate and the risk-based estimates, assuming that the latter estimates more closely approximate the true risk. A supralinear relationship between exposure and risk could also explain the difference, though this appears less probable. Otherwise, the risk-based estimates must substantially overestimate the true risk. Further research on the relative carcinogenicity of mainstream and sidestream smoke and the dose-response relationship for low exposures to tobacco smoke is necessary.

Effect of Past Exposures

One final problem needs to be addressed. The use of the average particulate ETS exposure for never smokers in 1980 will underestimate the average never smoker's risk if the smoker/never smoker exposure ratio was less in the past than in 1980, and if past exposures are more important in the development of lung cancer than recent exposures. The latter condition may not be true: the lung cancer risk for ex-smokers declines with the number of years since smoking ceased (SG, 1979). The former condition can be examined by estimating the change in exposure over time. The average smoker's past exposure can be determined from the average cigarette consumption and the average particulate delivery. Though the average

never smoker's past exposure cannot be estimated directly, it is possible to construct a relative exposure index from annual data on the average amount of tobacco in a cigarette, the percentage of the population that smokes, and the average cigarettes per day smoked per smoker.

Table 10 gives the average smoker's exposure as well as the average never smoker's exposure index for 1955, 1968, and 1980. The smoker's exposure has declined 60.4% since 1955 (mostly due to increased filter use), whereas the never smoker's exposure index has declined only 26.4%. The faster decline for smokers means that the 1980 smoker/never smoker exposure ratio is less than the ratio in 1955 (Table 10) and that the 1980 risk estimate for never smokers should overestimate the true risk based on a composite of past exposures.

The estimated average particulate ETS exposure for current smokers in 1980, based on machine-smoked particulate ETS deliveries, would overestimate the decline in the average smoker's exposure if each cigarette is smoked more intensely in 1980 than in 1955. However, the average smoker's exposure will decline faster than the never smoker's average exposure unless the average particulate ETS delivery/cigarette in 1980 is increased by 86% to 26.4 mg. An 86% average increase in the intensity with which each cigarette is smoked is unlikely; experimental studies of smokers given cigarettes with substantially lower tar and nicotine deliveries than their usual brand find the intensity of smoking to increase by 33% to 66% (Herning *et al.*, 1981; Ashton *et al.*, 1979).

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Appendix: Equations and Parameters of the Linear Extrapolation Estimate

Never Smoker's Retained Particulate ETS Exposure:

$$\text{Exp N} = \text{NRR}(\text{ExpH} + \text{ExpR} + \text{ExpW} + \text{ExpO})$$

where:

$$\text{Home Exposure (ExpH)} = R \times LH \times PH \times AH$$

$$\text{Restaurant/Bar Exposure (ExpR)} = R \times LR \times PR \times AR$$

$$\text{Work Exposure (ExpW)} = R \times LXW(PWW \times AWW + PBW \times ABW + PRW \times ARW)$$

$$\text{Other Exposure (ExpO)} = R \times LO \times PO \times AO$$

R = the respiration rate, Lx = the length of exposure in each location x, Px = the proportion of never smokers exposed to particulate ETS in each location x, Ax = the ambient particulate ETS level in each location x, WW = white-collar workplace, BW = blue-collar workplace, NRR = the never smoker particulate ETS retention rate.

Smoker's Retained Particulate Tobacco Smoke Exposure:

$$\text{ExpSM} = \text{SMRR}(\text{CPD} \times \text{TAR})$$

SMRR = the smoker particulate tobacco smoke retention rate, CPD = the average number of cigarettes smoked/day/smoker, TAR = the average tar delivery/cigarette.

Smoker's Lung Cancer Death (LCD) Rate:

$$\text{SMLCDR} = 100{,}000(\text{NSMLCD}/\text{SMPOP})$$

where:

$$\text{NSMLCD} = \text{TLCD} - \text{LCDN} - \text{LCDEX} - \text{LCDSM}$$

NSMLCD = the number of smoking-attributable LCDs among current smokers, SMPOP = the total number of current smokers, TLCD = the total number of LCDs in 1980, LCDN = number of LCDs which occurred among never smokers, LCDEX = number of LCDs which occurred among ex-smokers, LCDSM = number of LCDs which occurred among smokers from nonsmoking causes.

where:

$$\text{LCDEX} = (\text{TLCD} - \text{LCDN})/(1 + \text{NCS}/\text{NES} \times 2.26)$$

where:

NCS = the number of current smokers, NES = the number of ex-smokers.

Never Smoker's LCD Rate:

$$\text{NLCDR} = \text{SMLCDR}/(\text{ExpSM}/\text{ExpN})$$

SMLCDR = the LCD rate per 100,000 smokers, ExpSM = average smoker's particulate tobacco smoke exposure, ExpN = average never smoker's particulate ETS exposure.

Number of Never Smoker Lung Cancer Deaths from ETS Exposure:

$$= (\text{NPOP}/100{,}000)\text{NLCDR}$$

NPOP = number of never smokers, NLCDR = the lung cancer death rate per 100,000 never smokers.